

# Carbon nanotube scanning probe for profiling of deep-ultraviolet and 193 nm photoresist patterns

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The continual scaling down of complementary metal–oxide semiconductor feature size to 100 nm and below necessitates a characterization technique to resolve high-aspect-ratio features in the nanoscale regime. We report the use of atomic force microscopy coupled with high-aspect-ratio multiwalled carbon nanotube (MWCNT) scanning probe tip for the purpose of imaging surface profile of photoresists. MWCNT tips of 5–10 nm in diameter and about a micron long are used. Their exceptional mechanical strength and ability to buckle reversibly enable resolution of steep, deep nanoscale features. Images of photoresist patterns generated by 257 nm interference lithography as well as 193 nm lithography are presented to demonstrate MWCNT scanning probe tips for applications in metrology. © 2002 American Institute of Physics.  
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The metrology section of the International Technology Roadmap for Semiconductors (ITRS) roadmap<sup>1</sup> covers challenges ahead in microscopy, critical dimension (CD) overlay, film thickness and profile, and dopant profile among other issues. Microscopy is a core technology that provides images of the shape and appearance of various features in an integrated circuit. Typically microscopy is the first step, prior to measurement and process control, and as such, assumes enormous importance. In scanning electron microscopy (SEM), ultralow voltage electron beams are required to overcome image degradation due to charging and radiation damage to photoresist and other surfaces. Electron-beam induced damage to 193 nm resists has been recently reported.<sup>2</sup> As feature size continues to shrink, the edge brightness effect due to charging will also exacerbate and may limit the application of CD-SEM. Recently, atomic force microscopy (AFM) has emerged as a viable alternative to SEM. First, conductivity of the surface is irrelevant in using AFM. Second, AFM offers high resolution dictated by the size of the stylus. Finally, AFM operates in ambient environment, and the absence of vacuum requirements can lead to high throughput. There have been several recent studies on the use of AFM in metrology.<sup>3–6</sup> We discuss here the use of carbon nanotube (CNT) scanning probes for surface profiling of deep ultraviolet (DUV) and 193 nm photoresist patterns.

The pyramidal tip in the AFM cantilever is produced using microfabrication techniques including reactive ion etching to obtain the sharp tip. The tip typically is 10 nm or greater in diameter. In contact or tapping mode operation, the silicon tip can break or wear out while in use. Indeed it has been shown<sup>6</sup> that images obtained with a silicon probe in a

continuous scanning effort of a 2 nm silicon nitride surface exhibit variations in the image as a function of time; the grain size was found to be increasingly larger as time went on, which is undoubtedly due to the wearing of the tip. In contrast, the extraordinary strength and the ability to retain structural integrity after deformation make CNT scanning probes<sup>6–11</sup> robust and they turn out to be relatively hard wearing probes. Since the diameter of the tip determines the imaging resolution, CNT tips of 1–10 nm offer high resolution. Much progress on the fabrication of single-walled (SWCNT) and multiwalled CNT (MWCNT) probes has been reported recently<sup>6–10</sup> along with high lateral resolution images. The inherent problem of thermal vibration of the single-wall tips causes lateral image broadening as well as image blurring due to strong interaction with the substrate.<sup>11</sup> This problem can be mitigated by shortening the length of the SWCNT probe, depending on the nanotube diameter, to less than 100 nm (Ref. 9) or by using thicker multiwall probes.<sup>11</sup> MWCNT tips, with many layers of concentric nanotubes, suffer less from thermal vibrations. The tip vibration  $x_t$  is closely approximated<sup>9</sup> by  $x_t^2 = k_b T / k_{nt}$  where  $k_{nt} = 3\pi r^4 Y / 4l^3$ . Here,  $k_{nt}$  is the force constant for the lateral

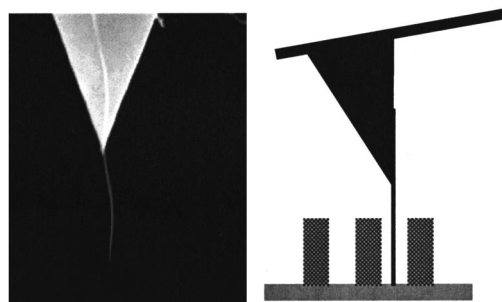


FIG. 1. SEM image of a MWCNT scanning probe (left-hand side) and a schematic showing the ability of a single MWCNT tip to trace the profile of trenches with deep and narrow features (right-hand side).

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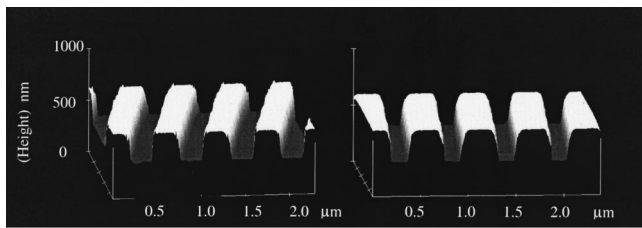


FIG. 2. AFM images, obtained with a MWCNT scanning probe, of DUV photoresist patterns generated by interferometric lithography with 257 nm irradiation. 500 nm pitch with an incident dose of 1.9 mJ/cm<sup>2</sup> (left-hand side) and 1.4 mJ/cm<sup>2</sup> (right-hand side).

bending of the nanotube,  $k_b$  is Boltzmann constant,  $T$  is temperature,  $Y$  is Young's modulus of the nanotube, and  $r$  and  $l$  are the radius and length of the nanotube probe, respectively. For the same small vibration (say  $x_t = 0.5$  nm), comparison of SWCNT and MWCNT tips gives  $l_m^3/l_s^3 = (r_m^4 Y_m)/r_s^4 Y_s$  with subscripts  $m$  and  $s$  denoting multiwalled and single-walled tips. Thus, the MWCNT probe can be longer than 1  $\mu$ m for a nanotube diameter of 10 nm without undergoing thermal vibration, which allows the probe to trace deep and narrow features.

In the present work, MWCNTs are prepared by chemical vapor deposition (CVD) and our approach has been described previously.<sup>12,13</sup> Our CVD reactor consists of a 1 in. quartz tube inserted in a high-temperature furnace. We use ethylene at 750 °C and atmospheric pressure to grow MWCNTs using iron catalysts. To prepare a MWCNT tip, we first prepare a cartridge containing MWCNTs grown by CVD and then transfer a tip to the cantilever by applying a dc field between the cantilever and the cartridge source as outlined in Ref. 10. Figure 1 shows a SEM image of a MWCNT tip used in this work. Note that our approach affords a single MWCNT as the tip, which is an improvement over the bundle of MWCNT tips in our ability to probe the increasingly narrow gap sizes in lithographic patterns (Fig. 1). A conventional laboratory AFM (Digital Instruments Nanoscope III multimode) in noncontact mode is used to generate the images.

To demonstrate the high-aspect-ratio imaging capability of a MWCNT tip, we have imaged patterns generated from photoresists relevant to future generations of silicon devices. The line/space arrays of positive-tone photoresists (used in DUV lithography) in Fig. 2 are patterned using 257 nm interference lithography.<sup>14</sup> The two arrays have 500 nm pitch

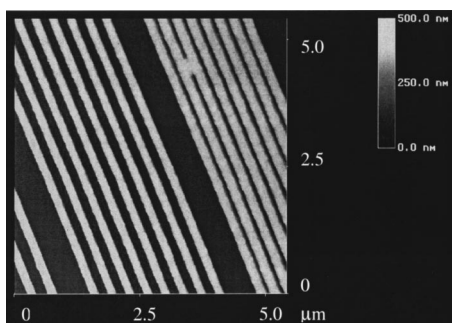


FIG. 3. AFM images with a MWCNT probe. Various line/space ratios are imaged.

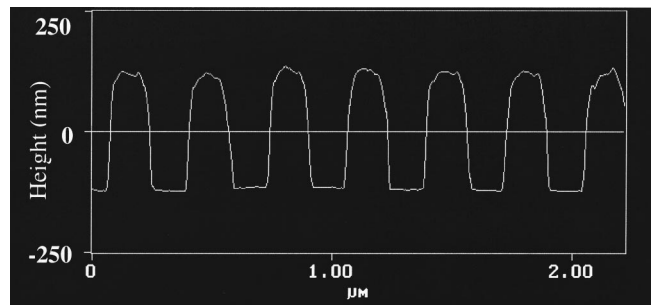


FIG. 4. Cross section profile of the 1:1 line/space array from Fig. 3.

line and space patterns but are exposed to different total incident irradiation doses of 1.9 and 1.4 mJ/cm<sup>2</sup>. As expected,<sup>14</sup> the higher dose gives a larger space width (230 nm versus 160 nm). The MWCNT probe is clearly able to resolve these narrow gap sizes. The scanning rate used in this work is 1 Hz.

Figure 3 shows an AFM image of a 193 nm IBM version 2 resist generated with a 193 nm exposure tool. The image shows a 130 nm linewidth with various line/space ratios. From the left- to the right-hand side, the line/space ratios are 1:1.5, 1:1, and 1:0.5 respectively. In the case of 1:0.5 ratio (see the far upper right-hand side of Fig. 3), part of the space is not opened and this microbridging is clearly resolved by the MWCNT probe. The cross section profile in Fig. 4 corresponds to the 1:1 array in Fig. 3 and shows a nearly vertical sidewall profile. This suggests that the interaction between the sidewall of the nanotube and the sidewall of the resist does not limit the imaging capability of the MWCNT tip. The slight asymmetry at the top of the profiles may be due in part to the limitations of the gain and feedback mechanism of our AFM. It is noteworthy that the MWCNT probe, in addition to its high resolution, circumvents the electron-beam damage reported for the CD-SEM technique and as evidenced from Figs. 2–4, does not appear to suffer from the instability and image blurring problems of SWCNT probes due to thermal vibration as discussed in Ref. 11.

In summary, we have demonstrated metrology application of MWCNT scanning probes in an AFM for imaging advanced technology photoresist patterns. In addition to the robustness of the MWCNTs as we have previously reported,<sup>6</sup> the probe also exhibits the ability to resolve features with high aspect ratio and can be a viable alternative to SEM as critical dimension metrology tool.

<sup>1</sup> See [http://public.itrs.net/Files/2001 ITRS/Home.html](http://public.itrs.net/Files/2001%20ITRS/Home.html) for 2001 ITRS Roadmap.

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